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Modified Atmospheric Density Model (MADM)

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14. ABSTRACT
Due to poor atmospheric density models for computing drag forces on satellites, AF Space Battlelab approved the initiative MADM. The Modified Atmospheric Density Model's objective is to update an atmospheric density model in near real-time using satellite-tracking data. This is accomplished by attempting to apply intelligent feedback from the empirical drag data for satellites in stable orbits to correct the overall atmospheric model density error. MADM uses an engineering approach, opposed to a scientific approach. MADM was able to reduce the modeled density error from approximately 15% to about 5% when applied to a study set of LEO satellites. This model density improvement dampened fluctuations in ballistic coefficients leading to an average improvement of about 200%. The final demonstrations showed that 80% of the overall catalog had improved prediction orbits in near real-time. Final operational processing techniques show significant promise, but will require some additional work.

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EXECUTIVE OVERVIEW

Modified Atmospheric Density Model (MADM)

Poor atmospheric density models for computing drag forces on satellites are a major source of inaccurate Low-Earth Orbit (LEO) satellite positions and reentry predictions. This deficiency can result in serious errors in the predicted position of satellites orbiting below 800 km altitude (many of these objects are of high interest in the Space Control mission).

Current atmospheric models do not accurately account for dynamic changes in atmospheric drag in orbit predictions. No significant improvements to atmospheric density models for space operations have occurred since the 1960s. Due to atmospheric complexity, model uncertainties, and space environmental forecast difficulty, reliable reentry and LEO satellite position predictions have been identified as one of the most challenging space operations deficiencies.

MADM was an approved AF Space Battlelab initiative designed to determine a new way of improving LEO orbit positioning predictions. The objective is to update an atmospheric density model in near real-time using satellite-tracking data. This is accomplished by attempting to apply intelligent feedback from the empirical drag data for satellites in stable orbits to correct the overall atmospheric model density error. The MADM approach is radically different from previous attempts to solve the atmospheric density problem since it uses an engineering, as opposed to a scientific, approach. Previous attempts at producing better models and new methods of calculation brought about only marginal improvements to the methods.

MADM clearly achieved its objective. MADM was able to reduce the modeled density error from approximately 15% to about 5% when applied to a study set of LEO satellites. This model density improvement greatly dampened fluctuations in ballistic coefficients leading to an average improvement of about 200%. The final demonstration showed that 80% of the overall catalog (with altitudes below 800 km) had improved prediction orbits in near real-time. Final operational processing techniques show significant promise, but will require some additional work.

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1. DEMONSTRATION MISSION STATEMENT

A. Purpose

The purpose of the MADM initiative is to demonstrate the ability to generate improved accuracy position predictions for Low Earth Orbit (LEO) satellites (under 800km altitude) by using enhanced atmospheric density calibration techniques. By deriving the atmospheric effects on calibration satellites, one can determine in near real-time the amount of drag the atmosphere is exerting on all objects which pass through the region. MADM is a proof-of-concept demonstration building upon work done from 1994 – 1996 by AFRL/VSBP with contract support from Radex, Inc, Science Applications International Corporation (SAIC) (under an SBIR contract) and SWC/AES.

A critical factor in predicting atmospheric effects is the ballistic coefficient. The ballistic coefficient is a number that reflects the amount of resistance or drag that an object experiences, for a given atmospheric density, as it passes through a medium (in the case of MADM, the upper atmosphere). The current orbit determination process estimates a ballistic coefficient which varies with time depending on whether the atmospheric model overestimates or underestimates the true atmospheric density. After applying the MADM atmospheric correction, the estimated ballistic coefficient becomes much closer to the true ballistic coefficient, thus improving the accuracy of the predicted trajectory.

B. Problem

Space surveillance is the cornerstone of space operations and involves the detection, tracking and maintenance of satellite trajectories. Knowing the exact location of a space object and being able to accurately predict its future position in space is critical to the Space Control mission. One of the major sources of error in predicting the positions of LEO satellites is relatively poor atmospheric density models. The general accuracy of these models has changed very little since the 1960s. Due to the high interest in many of these objects from the Space Control community, it is essential that accurate positions be maintained on these objects at all times.

Current atmospheric models do not accurately account for dynamic changes in atmospheric drag in orbit predictions. All orbit determination calculations assume the modeled density is accurate, and as a result, can produce poor quality position predictions. By monitoring the activity of a single calibration satellite and computing a correction to the atmosphere model density, subsequent orbit determination results in estimated ballistic coefficients much closer to the truth. This, together with improved state vector accuracy, results in more accurate predicted positions.

C. Objectives

MADM is an approved AF Space Battlelab initiative designed to demonstrate a new way of improving LEO satellite position predictions. The objective is to update an atmosphere model in near real-time using satellite-tracking data. This is accomplished by attempting to apply intelligent feedback from the empirical drag data for satellites in stable orbits to correct the overall atmospheric model density error. The MADM approach is radically different from previous attempts to solve the atmospheric density problem. MADM uses a near real-time update approach as opposed to a climatological approach. Previous attempts at better climatological models and associated methods of calculation brought about only marginal improvements to the methods. The following MADM objective was met:

Demonstrate the ability to generate improved accuracy position predictions for low earth orbit satellites (under 800 km altitude) by using enhanced atmospheric density calibration techniques.

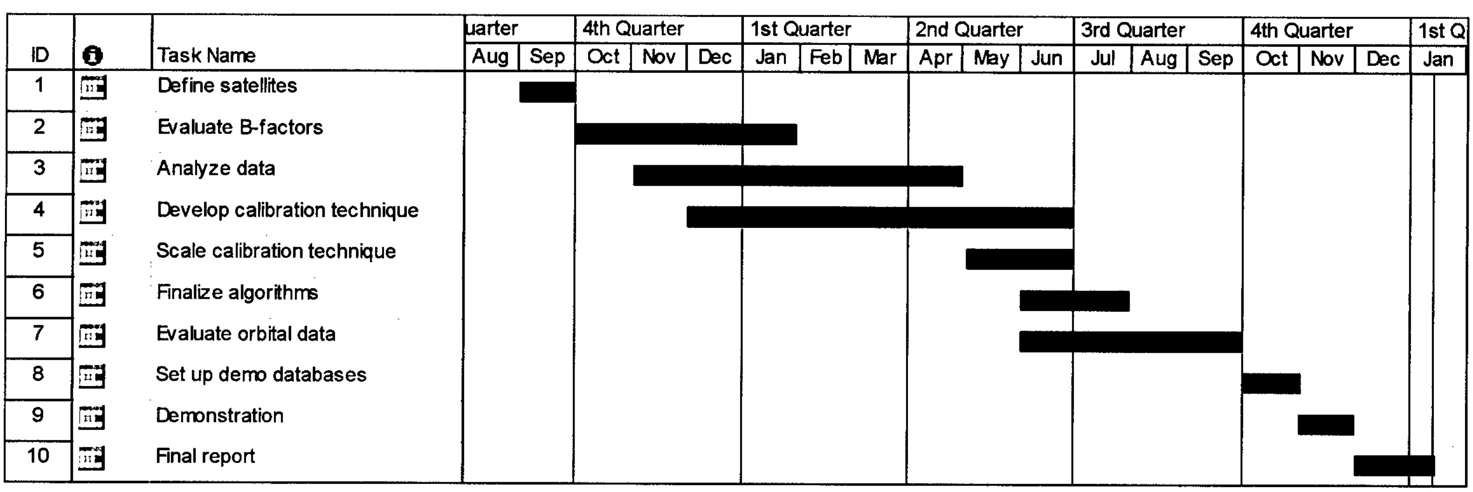
D. Length of Time

1. Submittal of Battlelab Initiative to Approval

Based on the successful work initiated by AFRL, Dr. Joseph Liu, HQ SWC/AE, submitted the initial concept of MADM to the Air Force Space Battlelab (SB) on 20 Jan 98. The SB presented the MADM concept to the Battlelab Planning Cell (BPC) on 25 Jun 98. The SB General Officer Advisory Group (GOAG) approved the MADM concept for detailed planning on 8 Jul 98 and execution on 24 Aug 98. The SB allocated $500K total for the project ($90K in FY 98, $410K in FY 99). An additional $45K was invested in the project in FY 00 due to final demonstration rescoping.

2. From Approval to Completion

MADM commenced on 24 Aug 98 and was completed on 15 Jan 00. The following is the detailed schedule and timeline for the project:



2. COURSE OF ACTION

A. Overview

The SB worked with several different Government organizations and contractors to complete this successful project. The AFRL/VSBP and their Radex, Inc. contractor performed data analysis and the MADM technique development. Science Applications International Corporation (SAIC) generated significant analysis and data to support AFRL and ITT efforts. SAIC also provided expertise and software development support. ITT Industries, Space Division, provided integration and proof of concept support. The National Reconnaissance Office (NRO) provided advisement and equipment. Finally, Space Warfare Center, Analysis & Engineering provided critical technical expertise and advisement. Participant final reports are at Attachments A - F.

The goal of the project was to have MADM software immediately available for integration and operational implementation with the destination of the modified code being SWC/AE's Astrodynamic Software Workstation (ASW). The MADM concept is one of the critical building blocks needed in the progression toward a higher fidelity Dynamic Calibration Atmosphere (DCA) approach.

B. Demonstration Description

1. Select Evaluation Satellite Sample

The first step in the project was to select a sample set of LEO satellites for study. From this data set, the ballistic coefficients, solar & atmospheric conditions and other historical data were collected, derived and studied.

Ninety-five satellites were selected by SWC/AE to be used in the study set for MADM concept development. Many of the satellites in the set had to be eliminated due to one or more reasons: altitudes were too high, large historical data gaps, improper observation tagging, etc. The final sample set consisted of 32 satellites.

2. Develop Global Calibration Technique

Based on the results of the sample satellite study, atmospheric density corrections were developed and existing code modified. Techniques for globalizing the models were proposed. The initial design specified the use of 20 or more satellites to be real-time data collectors. However, work completed by AFRL/VSBP revealed that one satellite's feedback could effectively give a global estimate of current atmospheric conditions.

3. Finalize Model and New Code

SAIC had the task of performing a final analysis of the code and converting it into useful form. Once complete, the code package was delivered to ITT.

4. Demonstrate MADM Utility

ITT had the task of running the final demonstration to determine the improvements made by MADM. The final demonstration consisted of running 70 days worth of the entire satellite catalog (with perigee altitudes below 800 km) with and without the MADM corrections. Also a subset of 36 high drag satellites were run using the same method. The results of the two runs were compared to gain an understanding of the improvements fostered by MADM.

The unit used to measure MADM performance is Error Growth Rate (EGR). EGR is the increase in error when measured against truth data. A technical definition of EGR is the slope of the line between a time and position error axis. Therefore, EGR was measured in units of kilometers per day.

5. Changes to Demonstration

The final demonstration of MADM was modified during the course of the initiative execution. Originally, the plan called for a demonstration of MADM's capabilities by using the Starfire Optical Range laser to laze a satellite more accurately. After analysis later in the course of the project, the MADM team determined that there were many other factors that would affect the accuracy of pointing the laser, and that this particular proposed MADM demonstration venue would not conclusively highlight the project's improved capability.

Another of the original goals was to assess MADM's impact on predicting the decay of satellites. This portion of the project was also deemed inappropriate later in the project. As a satellite decays, numerous other factors affect its final path. As such, the effect of MADM on these types of objects could not clearly be determined.

3. RESULTS

The MADM demonstration was very successful in meeting the stated objective. The error in the modeled ballistic coefficient was decreased by approximately 65%.

The most significant accomplishment of the project was the dramatic improvement in the ability to produce more accurate ballistic coefficients. Most satellites experience an average density error of 15%. By using the MADM technique, the density error was reduced to 5% or below, a 200% increase in accuracy. The variability of the estimates for the ballistic coefficient has been significantly reduced, providing a better fit to real world physics while decoupling the drag prediction from the error in atmospheric density prediction.

The MADM technique also appears to have a significant effect on 12-hour and 6-hour satellite position prediction accuracy. This also shows promise for significant operational utility.

The results of the final demonstration also give credence to the MADM concept. For the full catalog comparison, 80% of the catalog had improved EGR, and 20% had degraded EGR. The average improvement to the EGR was approximately 100 m per day. The results clearly indicate that MADM had a significant effect on improving the entire catalog.

SAIC also re-ran some of the ITT test cases using more suitable calibration satellites and using a sequential orbit determination process with a 1-day lag instead of a 2-day lag. SAIC found that the MADM technique improved the orbits of eight or nine satellites. The results were significantly improved and are shown in Attachment G.

4. RECOMMENDATIONS

A. Continue work to determine best operational processing methods. Batch processing and sequential processing both need to be explored and run against a truth data set to determine the optimal approach.

B. Press for formulating a version of MADM that can be operationally approved and implemented in the Astrodynamic Support Workstation (ASW).

C. Continue with a joint development team. The expertise for atmospheric calibration resides in numerous organizations, including Government, industry and academia.

D. Maintain a density calibration test bed to improve the MADM technique.

E. Pursue promising alternative (but compatible) algorithms and consider replacing or adding to the MADM technique.

- Incorporate multiple satellites to calculate global neutral density.
- Eliminate time lagging in the current method of calculating the correction.
- Make use of predicted solar flux and geomagnetic index.

5. CONCLUSION

The MADM project demonstrated an improved technique to predict the orbits of LEO satellites. Significant progress was achieved in consistently generating improved LEO satellite ballistic coefficients as well as the other state vector components. With improved ballistic coefficients, average error corrections can be applied to LEO satellites resulting in improved orbit predictions. While MADM is close to becoming operationally implementable, additional work needs to be done to determine the optimal back-end processing for satellite catalog maintenance and special tasks.

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